Towards a Theory of High Confidence Networked Control Systems: Action Webs

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August 9th, 2011

Joint work with Saurabh Amin and Galina A. Schwartz

4th International Symposium on Resilient Control Systems

Outline

Motivation: Cyber-Security

Sensor networks & Networked Control Systems (NCS)

NCS vulnerabilities

Cyber-security for NCS

1. Threat assessment
2. Attack diagnosis
3. Resilient control

Conclusions and ongoing work

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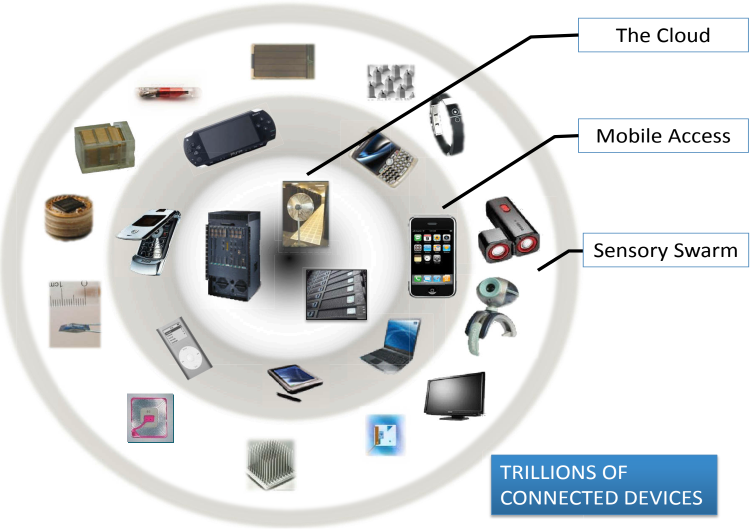
The swarm at the edge of the cloud

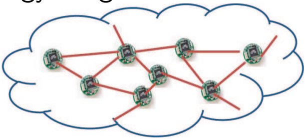


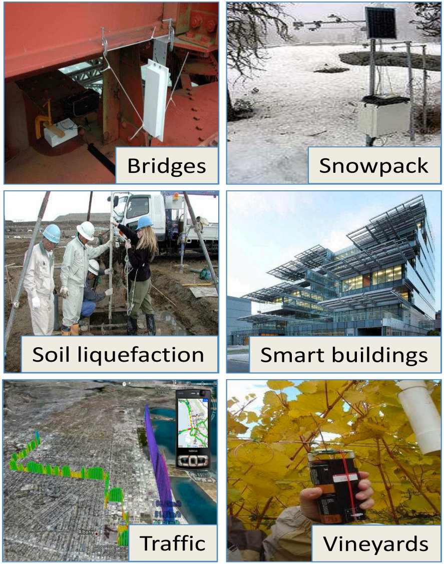
Source: J. Rabaey [ASPDAC'08]

Ubiquitous instrumentation

Wireless Sensor Networks (WSN) for infrastructure monitoring

- Environmental systems
- Structural health
- Construction projects
- Energy usage





Courtesy: UCB-CEE Systems Faculty

Sensor webs everywhere

Change detection: Thresholds, phase transitions, anomalies

- Security systems
- Health care
- Wildfire detection
- Fault diagnosis
- Tracking & surveillance

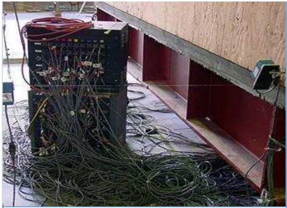
Widely deployed in critical infrastructures

Supervisory Control & Data Acquisition (SCADA)

- Robust estimation
  - Noisy measurements
  - Lossy communication
- Real-time control
  - Safety
  - Performance

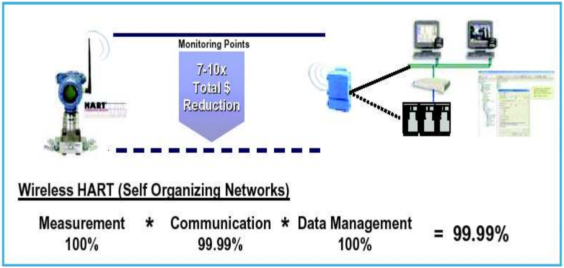
COTS IT for SCADA

- Cost ↓, Reliability ↑
- Digital and IP based: New vulnerabilities!
- Reliability $\not\Rightarrow$ Security



Wired networks are costly to maintain

Typical industrial infrastructure ~ $10B



Source: Emerson case study

Societal cyber-physical systems

A complex collection of sensors, controllers, compute nodes, and actuators that work together to improve our daily lives

- From very small: Ubiquitous, Pervasive, Disappearing, Perceptive, Ambient
- To very large: Always Connectable, Reliable, Scalable, Adaptive, Flexible

Emerging Service Models

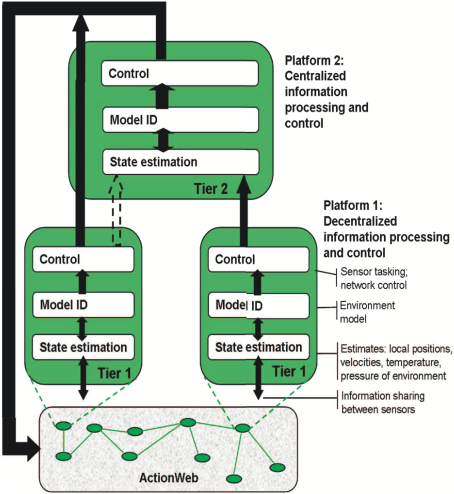
- Building energy management
- Automotive safety and control
- Management of metropolitan traffic flows
- Distributed health monitoring
- Smart Grid

Action Webs

Observe and infer for planning and modifying action

- Dealing with uncertainty
- Tasking sensors
- Programming the ensemble
- Multiple objectives
- Embedding humans

Example: Building energy management

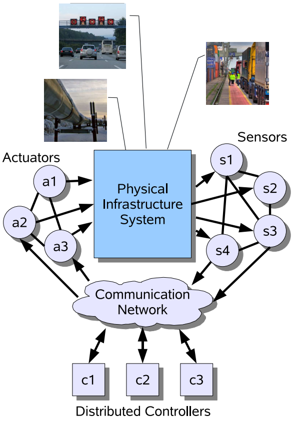


Courtesy: Claire Tomin

Challenges for Action Webs

High confidence networked control

- Robust estimation
  - Unreliable communications
  - Mobile sensor & actuator dynamics
  - Distributed parameter systems
- Fault-tolerant networked control
  - Limits on stability, safety, & optimality
  - Scalable model predictive control
- Security & resilience [Focus of this talk]
  - Availability, Integrity, & Confidentiality
  - Graceful degradation



Cyber-attacks to NCS

Maroochy Shire sewage plant *(2000)*

Los Angeles traffic control *(2008)*

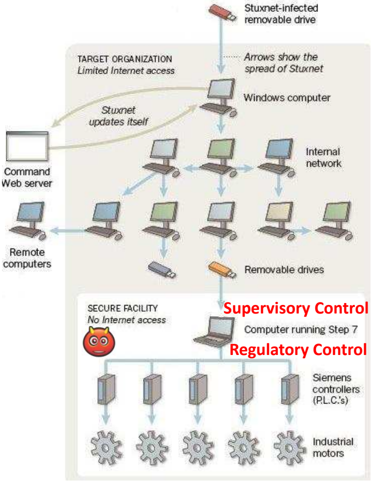
Tehama Colusa canal system *(2007)*

Cal-ISO power system computers *(2007)*

NCS security concerns

Attackers

- Malicious insiders
- Computer hackers
    - Cyber criminals
    - Cyber warriors
    - Hacktivists
    - Rogue hackers
    - Corporate spies



Source: Symantec, NYT

Stuxnet worm

- Targets SCADA systems
- Four zero-day exploits, antivirus evasion techniques, p-2-p updates, network infection routines
- Reprograms *Programmable Logic Controller (PLC)* code

Previous work in WSN security

1. Secure communication
   - SPINS: Security protocols for WSNs (Perrig, Culler, Tygar)
   - TinySec: Link layer encryption (Karlof, Sastry, Wagner)
2. Robust aggregation
   - SIA: Secure Information Aggregation (Przydatek, Song, Perrig)
   - Resilient Aggregation (Wagner)
3. Sybil Attack
   - Countermeasures (Newsome, Shi, Song, Perrig)
4. Secure location verification
   - Verification of location claims (N. Sastry, Wagner)
5. Robust localization
   - Statistical methods for robust localization (Li, Trappe, et.al.)
   - SeRLoc (Lazos, Poovendran)
6. Cryptographic Key distribution protocols
   - Random key distribution protocol (Perrig, Song, Gligor)

Previous work in security is not enough

Missing:	• How is data collected by NCS used? • Resilient control & anomaly detection for NCS
System Design	• Least Privilege Principle • Separation of Duty
Software Validation	• Correct implementation of system design • Minimize vulnerabilities and bugs
Network Security	• End-to-end integrity, confidentiality, availability • Network intrusion detection
Device Security	• Trusted Platform Modules (TPM): device integrity

Courtesy: A. Cárdenas

Cyber-security for NCS

Classical approaches

- Cyber: Computer (IT) security
  - Prevention, detection, and resilience mechanisms
- Physical: Robust (fault-tolerant) control
  - Trade-offs: Cost vs. Robustness [to random disturbances]

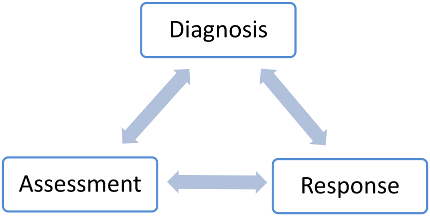
Open questions

- Effect of cyber-attacks on control algorithms?
- Faults vs. Attacks?
- Reliability vs. Security?
- Individual vs. Social incentives [to secure]?

Proposal: Robust control + IT security $\Rightarrow$ NCS security

Cyber-security for NCS: three problems

1. Threat assessment
   - How to model attacker and his strategy?
   - Consequences to the physical infrastructure
2. Attack diagnosis
   - How to detect manipulations of sensor-control data?
   - Stealthy [undetected] attacks
3. Resilient control
   - Design of resilient control algorithms?
   - Incentive mechanisms to improve NCS reliability & security



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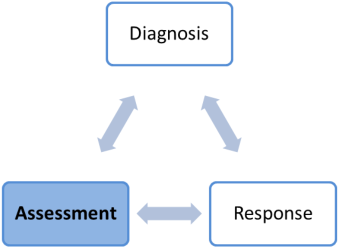
Threat assessment

- How to model attacker and his strategy?
- Consequences to the physical infrastructure



Field operational test on the Gignac canal network
[Amin, Litrico, Sastry, Bayen. HSCC'10]

Models of deception and denial-of-service (DoS) attacks
[Amin, Cárdenas, Sastry. HSCC'09]

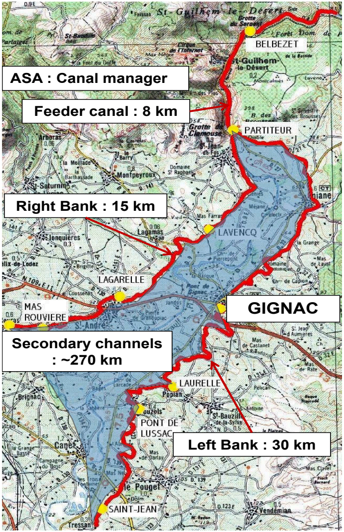
Assessment for Tennessee Eastman process control system (TE-PCS)
[Cárdenas, Amin, Lin, Huang, Sastry. ASIACCS'11]

Gignac water canal network

SCADA components

- Level & velocity sensors
- PLCs & gate actuators
- Wireless communication
- Multiple stakeholders

Communication station



Map of Gignac canal

Presented by permission from Cemagref, France

Gignac canal network

Physical infrastructure

Cyber infrastructure

Reported attacks on water SCADA systems

Gignac canal system attacks

- Stealing water by compromising sensors
- Tampering PLCs
- Theft of solar panels

Other SCADA vulnerabilities

- Time between telemetry requests can be used for malicious traffic injection
- Encryption provides confidentiality but does not provide data integrity

Gignac **Le canal victime d'actes de vandalisme à répétition**

Depuis le 21 juin, le canal de Gignac est victime d'actes malveillants sur l'ouvrage de l'aqueduc de l'Aurelle (derrière le lagunage de Popian) : effondrement du radier du canal puis dégradation des réparations mises en place (retrait des boulots de serrage, mettant gravement en péril la pérennité de l'aqueduc).
L'ouvrage de l'Aurelle permet la continuité du transport de l'eau vers les parcelles du périmètre irrigué situé sur les communes de Pouzols, Le Pouget, Tressan et Puilacher, soit près de 900 ha, pour lesquels l'apport d'eau estival est essentiel.
Ces agissements ont fait l'objet de constats par les brigades de gendarmerie et de plaintes contre X. Il est à noter que l'intégralité du patrimoine de l'Association syndicale autorisée du canal de Gignac est un ouvrage public, dont la destruction, la dégradation ou la détérioration peuvent faire l'objet de poursuites et être punies de trois ans d'emprisonnement et de 45 000 € d'amende.

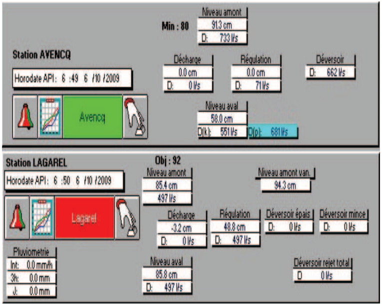
Courtesy: C. Hugodot, Manager

Regulatory control of canal pools

Control objective

- Manipulate gate opening
- Control upstream water level
- Reject disturbances (offtake withdrawals)

SCADA interface



Avencq cross-regulator

Defender and attacker models

Defender

- Estimate Model [Freq. Domain]

$$\hat{y}_i^d = \frac{a_i^d}{s} e^{-\tau_i s} \hat{q}_{i-1} - \frac{a_i^d}{s} [\hat{q}_i + \hat{p}_i]$$

Parameters: a_i^d, τ_i, Laplace variable: s

- Design robust decentralized PI control

$$\hat{q}_{i-1} = \kappa_{i-1i} \hat{y}_i^d, \quad \hat{q}_i = \kappa_{ii} \hat{y}_i^d$$

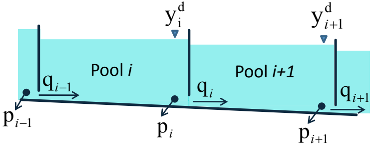
Controllers: $\kappa_{i-1i}, \kappa_{ii}$

Attacker

- Compromise y_i^d and inject g_i

$$\tilde{y}_i^d = y_i^d + g_i$$

- Regulate p_i to steal water

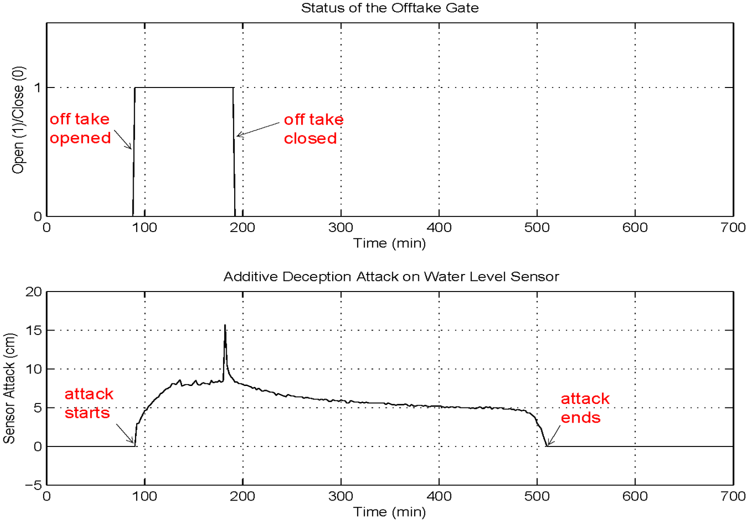


Test site before attack

Test site after attack

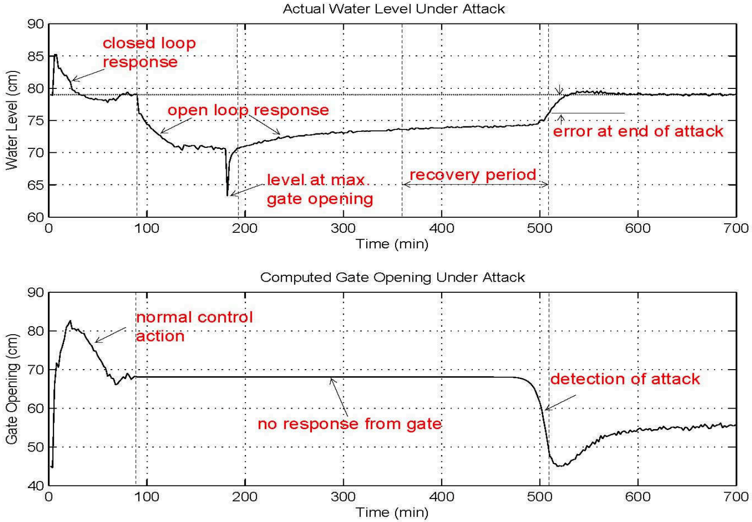
Cyber-attack on the Avencq canal pool

Field operational test (October 12th, 2009)



Cyber-attack on the Avencq canal pool

Successful attack



Cyber-attacks on NCS

Cyber Attacks

SCADA Manager [IT Security] **A6**

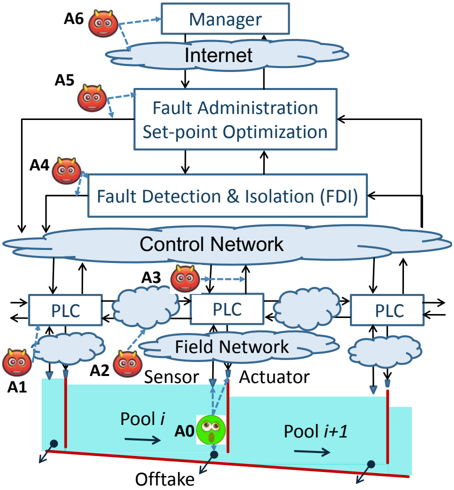
- Unauthorized access, Viruses

Supervisory Control **A3-A5**

- Deception: set-point change, parameter substitution
- Denial-of-Service (DoS): network flooding, process disruption

Regulatory Layer **A1-A2**

- Deception: compromise of measurements & controls, spoofing, replay
- DoS: jamming, $\uparrow$ comm. latency

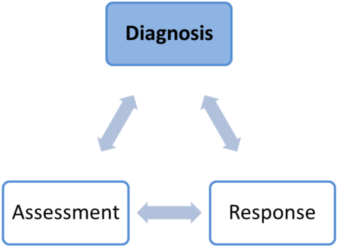


Physical Faults [Control th.] **A0**

- Sensor-actuator faults
- Unauthorized leaks

Attack diagnosis

- How to detect manipulations of sensor-control data?
- Stealthy [undetected] attacks



Observer-based diagnosis for Gignac SCADA system
[Amin, Litrico, Sastry, Bayen. IEEE TCST'11]

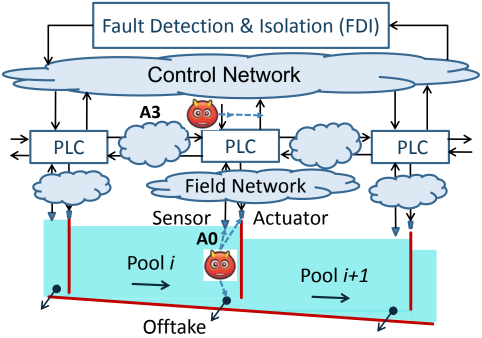
Non-parametric CUSUM statistic based diagnosis for TE-PCS
[Cárdenas, Amin, Sastry, et.al. ASIACCS'11]

Study of stealthy attacks on power system state estimators
[Teixeira, Amin, Sandberg, Johansson, Sastry. IEEE CDC'10]

Attacks on supervisory control layer

Supervisory Layer Attacks **A3**

- Deception: set-point change, parameter substitution
- Denial-of-Service (DoS): network flooding, process disruption

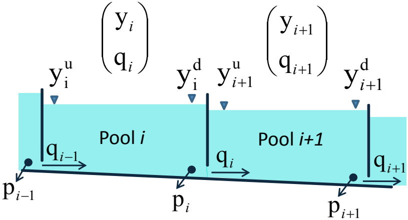


Physical Faults/Attacks **A0**

- Sensor-actuator faults
- Unauthorized withdrawals

Design of a model-based diagnosis scheme

Flow model



Linear hyperbolic conservation laws

$$\partial_t \xi_i(t,x) + A(x)\partial_x \xi_i(t,x) + B(x)\xi_i(t,x) = 0,$$

- State: $\xi_i = \begin{pmatrix} y_i, & q_i \end{pmatrix}^\top$
- Domain: $x \in (0, l_i)$, $t \geqslant 0$
- Boundary conditions
  1. $q_i(t,0) = q_{i-1}$
  2. $q_i(t,l_i) = q_i + p_i(t)$
- Initial conditions
  1. $y_i(0,x) = \bar{y}_i(x)$
  2. $q_i(0,x) = \bar{q}_i(x)$

Variables

Measurements

- Upstream level: y_i^u
- Downstream level: y_i^d

Controls

- Upstream discharge: q_{i-1}
- Downstream discharge: q_i

Disturbances

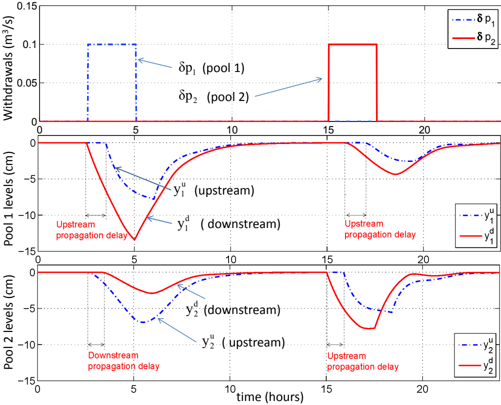
- Offtake withdrawal: p_i

Finite-dimensional [approximate] model

Delay Differential System

$$\dot{x}(t) = \sum_{i=0}^{r} A_i x(t-\tau_i) + \sum_{i=0}^{r} B_i u(t-\tau_i) + \sum_{i=1}^{r} E_i f_i(t)$$

$$y(t) = Cx(t)$$



For two-pool system:

- State $x := \left(y_1^u, \quad y_2^u, \quad y_1^d, \quad y_2^d\right)^T$
- Input $u := \left(u_0, \quad u_1, \quad p_1, \quad p_2\right)^T$
- Output $y := \left(y_1^u, \quad y_2^u, \quad y_1^d, \quad y_2^d\right)^T$
- Unauthorized withdrawals $f_i(t) := \left(\delta p_i(t), \quad \delta p_i(t-\tau_i)\right)^T$

State Estimation

System

$$\dot{\mathrm{x}}(t) = \sum_{i=0}^{r} A_i \mathrm{x}(t-\tau_i) + \sum_{i=1}^{r} B_i \mathrm{u}(t-\tau_i) + E\mathrm{f}(t)$$
$$\mathrm{y}(t) = C\mathrm{x}(t) + H\mathrm{g}(t)$$

- f: unauthorized withdrawals
- g: deception attack on sensors

Unknown Input Observer (UIO)

$$\dot{\mathrm{z}}(t) = \sum_{i=0}^{r} F_i \mathrm{z}(t-\tau_i) + \sum_{i=0}^{r} TB_i u(t-\tau_i) + \sum_{i=0}^{r} G_i \mathrm{y}(t-\tau_i)$$
$$\hat{\mathrm{x}}(t) = \mathrm{z}(t) + N\mathrm{y}(t)$$

- F_i, G_i, T, N: unknown matrices
- z: observer state
- $\hat{\mathrm{x}}$: state estimate

Diagnosis scheme for unauthorized withdrawals

Unknown Input Observer (UIO): design problem

For $\mathsf{f} \equiv \mathsf{g}$, find F_i, G_i, T and N such that $\hat{\mathsf{x}}(t)$ asymptotically converges to $\mathsf{x}(t)$, regardless of unauthorized withdrawals $\mathsf{f}(t)$.

Theorem

An asymptotically stable UIO exists if

$$\operatorname{rank}\begin{pmatrix} CE \\ H \end{pmatrix} = \operatorname{rank}\begin{pmatrix} E \\ H \end{pmatrix},$$

& set of delay-dependent linear matrix inequalities are feasible. □

(Amin, Litrico, Sastry, Bayen. IEEE TCST I, II (2011))

Diagnosis scheme using the bank of two-observers

Observer residuals $\mathsf{r}_j(t) := \mathsf{y}_j(t) - C\hat{\mathsf{x}}_j(t)$, $j = 1, 2$

If	$\lVert \mathsf{r}_1 \rVert$	$\lVert \mathsf{r}_2 \rVert$
$\mathsf{f}_1 \neq 0$	≈ 0	$\neq 0$
$\mathsf{f}_2 \neq 0$	$\neq 0$	≈ 0

Diagnosis of unauthorized withdrawals: no attack

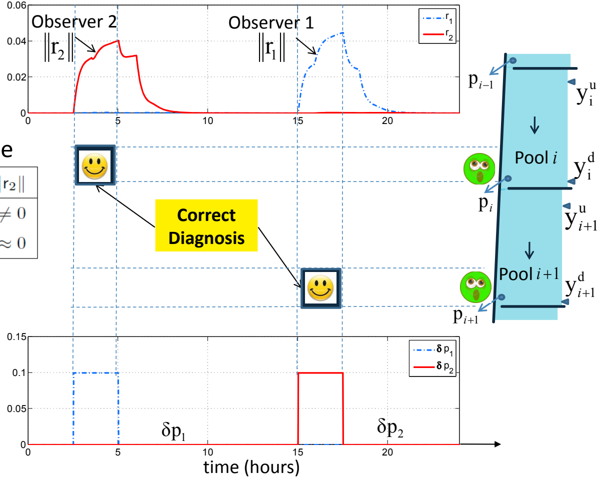
Sensors: y_i^d, y_{i+1}^d and y_i^u, y_{i+1}^u

Decision rule

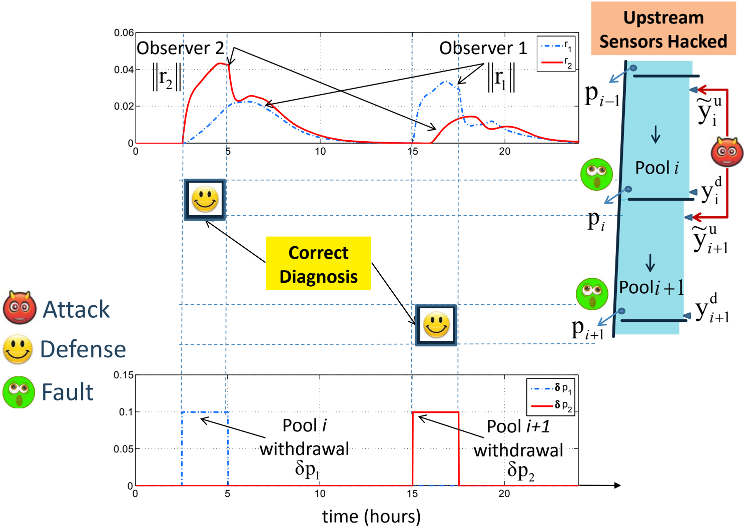
If	$\|r_1\|$	$\|r_2\|$
$f_1 \neq 0$	≈ 0	$\neq 0$
$f_2 \neq 0$	$\neq 0$	≈ 0

Defense

Fault

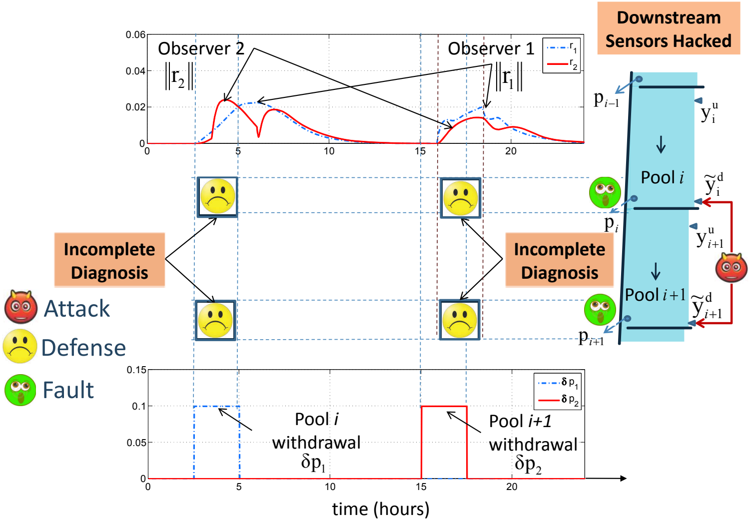


Attack diagnosis: upstream level sensors hacked



Correct diagnosis of withdrawal in both pools

Attack diagnosis: downstream level sensors hacked



Withdrawal detected in both pools

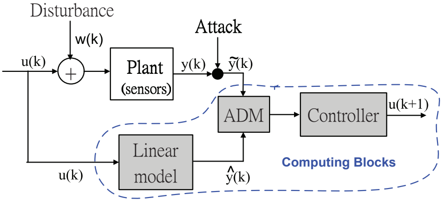
Security Implications

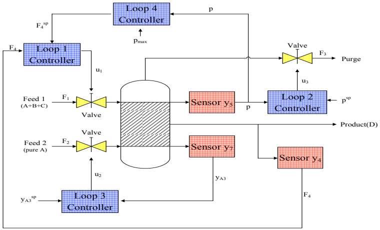
Recommendations to the European Commission on Canal Automation & the Cemagref Research Institute

- Enhanced model (redundancy) improves detection
- Sensors located closer to the offtakes are critical
- Localized sensor attacks do not lead to global degradation
- Multiple pool sensor attacks can evade detection [stealth]

Attack Diagnosis for [other] SCADA systems

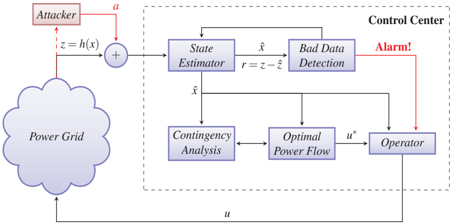
Process control

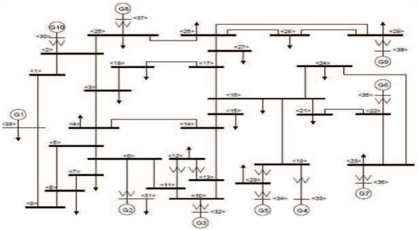




[Cárdenas, Amin, Lin, Huang, Sastry. ASIACCS'11]

Power transmission

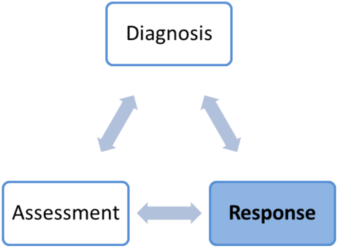




[Teixeira, Amin, Sandberg, Johansson, Sastry. IEEE CDC'10]

Resilient control

- Design of resilient control algorithms?
- Fundamental limitations & interdependent security



Stability of hyperbolic PDEs under switching boundary control
[Amin, Hante, Bayen. IEEE TAC'10]

Incentives to secure under network induced interdependent risks
[Amin, Schwartz, Sastry. GameSec'10]

Safety-preserving control for stochastic systems under comm. losses
[Amin, Cárdenas, Sastry. HSCC'09]

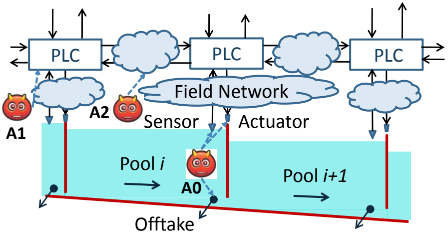
Attacks on regulatory control layer

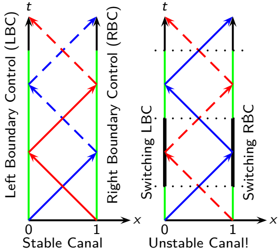
Regulatory layer **A1-A2**

- Deception: compromise of measurements & controls
- DoS: jamming, ↑ latency

Physical faults or attacks **A0**

- Sensor-actuator faults
- Unauthorized withdrawals





Switching attacks can lead to instability!

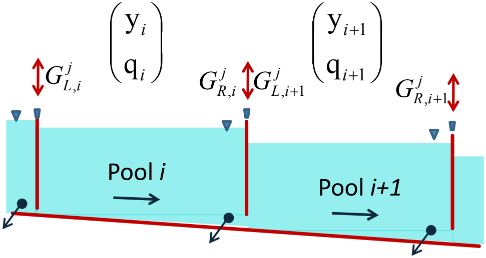
Attack model: Switching system of PDEs

Switching attack model

$$\partial_t \xi(t,x) + A^j(x)\partial_x \xi(t,x) + B^j(x)\xi(t,x) = 0,\ x \in (a,b),\ t > 0$$

$$\xi_{II}(t,a) = G_L^j \xi_I(t,a), \quad \xi_I(t,b) = G_R^j \xi_{II}(t,b),\ t \in [0,\infty)$$

$j \in \mathscr{Q}$, where $\mathscr{Q} = \{1,\ldots,N\}$ is the set of attacker strategies.



Switching attacks: investigation of system stability

Switching attack: stability

Consider a switching attack $\sigma(\cdot) : \mathbb{R}_+ \to \mathscr{Q}$ on the system:

$$\partial_t \xi(t,x) + A^{\sigma(t)}(x)\partial_x \xi(t,x) + B^{\sigma(t)}(x)\xi(t,x) = 0, \; x \in (a,b), \; t > 0$$
$$\xi_{II}(t,a) = G_L^{\sigma(t)} \xi_I(t,a), \quad \xi_I(t,b) = G_R^{\sigma(t)} \xi_{II}(t,b), \; t \in [0,\infty)$$

Theorem

Let A^j be diagonal or pairwise commute, and boundary data satisfy:

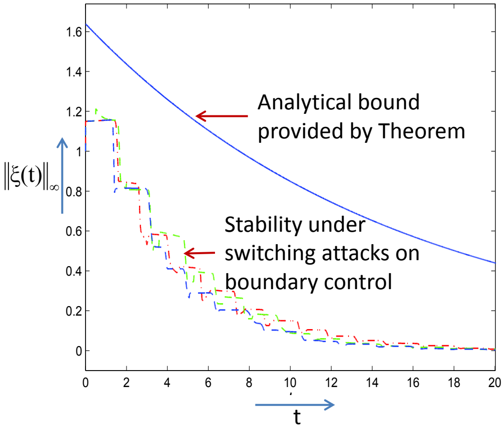
$$\max_{j,j' \in \mathscr{Q}} \rho \left(\begin{bmatrix} 0 & |G_R^{j'}| \\ |G_L^j| & 0 \end{bmatrix} \right) < 1.$$

Then there exists $\varepsilon > 0$ such that for $\|B^j(x)\|_\infty \leqslant \varepsilon$, the system is exponentially stable under an arbitrary switching attack. □

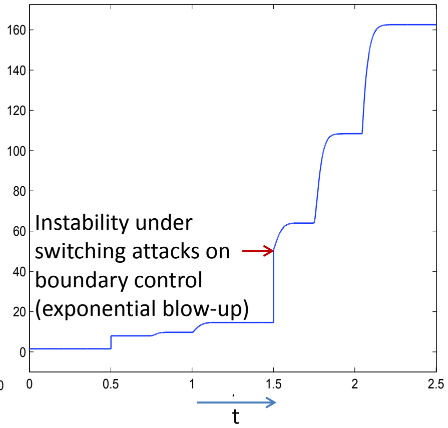
[Amin, Hante, Bayen. HSCC'08, IEEE TAC'10]

Switching attack: characterization of system stability

All assumptions of stability thm. hold



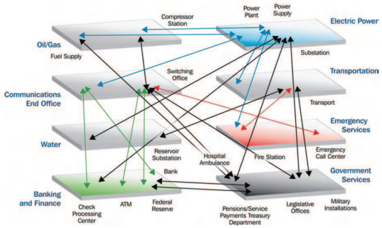
An assumption of stability thm. violated



Interdependent Security (IDS) & incetives to secure

Security interdependencies due to

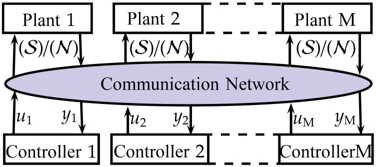
- Network induced risks
  - ⇒ Example: Distributed DOS attacks
- Wide use of COTS IT components
  - ⇒ Expect increased interdependencies



Infrastructure interdependencies

Interdependent security

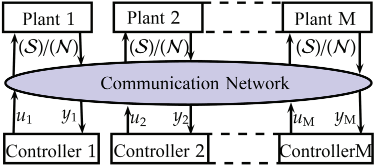
- Goal: Security analysis & implementation of control measures
- Methods: Game theory & Control theory
- Observation: Individual & social incentives differ



Network induced interdependencies

Interdependent NCS

Two-stage game of plant-controller systems (players)



Each player

1. Invests in security $[V^i = S$ & incurs $\ell^i > 0]$ or not $[V^i = N]$
2. Chooses inputs u_t^i for NCS:

$$x_{t+1}^i = Ax_t^i + \nu_t^i B u_t^i + w_t^i$$
$$y_t^i = \gamma_t^i C x_t^i + v_t^i$$

where γ_t^i & ν_t^i are Bernoulli packet loss processes

Interdependent failure probabilities

- Failure probabilities:

$$P[\gamma_t^i = 0 \mid V] = \tilde{\gamma}^i(V), \quad P[\gamma_t^i = 1 \mid V] = 1 - \tilde{\gamma}^i(V),$$

  - $V := \{V^1, \dots, V^{\mathrm{m}}\}$ Set of player security choices
- Security choices and failure probabilities:

$$\tilde{\gamma}^i(V) = \underbrace{\mathbf{1}_S^i \bar{\gamma}^i}_{\text{reliability}} + \underbrace{(1 - \mathbf{1}_S^i \bar{\gamma}^i)\beta(\eta^i)}_{\text{security}},$$

  - $\mathbf{1}_S^i$: Indicator function 1 if $V^i = S$
  - η^i: # of insecure players
  - $\beta(\eta^i)$: Interdependence term

$$0 < \beta(\{S, \dots, S, \underbrace{N \dots, N}_{\eta \text{ players}}\}) < \beta(\{S, \dots, S, \underbrace{N \dots, N}_{\eta+1 \text{ players}}\}) < 1,$$

Multiplayer game with interdependent security

- $V := \{V^1, \ldots, V^{\mathrm{m}}\}$ Set of player security choices
- $U := \{u_t^1, \ldots, u_t^{\mathrm{m}} | t \in \mathbb{N}_0\}$ Set of player control input sequences
- Each player minimizes his total cost:

$$J^i(V,U) = J^i_{\mathrm{I}}(V) + J^i_{\mathrm{II}}(V,U),$$

1. Security cost

$$J^i_{\mathrm{I}}(V) := (1 - \mathbf{1}^i_S)\ell^i$$

2. LQG control cost:

$$J^i_{\mathrm{II}}(V,U) := \limsup_{T \longrightarrow \infty} \frac{1}{T} \mathsf{E}\left[\sum_{t=0}^{T-1} x_t^{i\top} G x_t^i + v_t^i u_t^{i\top} H u_t^i\right]$$

- Social planner minimizes the aggregate cost:

$$J^{\mathrm{SO}}(V,U) = \sum_{i=1}^{\mathrm{m}} J^i(V,U).$$

Increasing and decreasing incentives to secure

2−player game

	S	N
S	$J^*_{\mathbb{II}}(\{S,S\})+\ell^1,\ J^*_{\mathbb{II}}(\{S,S\})+\ell^2$	$J^*_{\mathbb{II}}(\{S,N\})+\ell^1,\ J^*_{\mathbb{II}}(\{N,S\})$
N	$J^*_{\mathbb{II}}(\{N,S\}),\ J^*_{\mathbb{II}}(\{S,N\})+\ell^2$	$J^*_{\mathbb{II}}(\{N,N\}),\ J^*_{\mathbb{II}}(\{N,N\})$

Increasing incentives

If a player secures, other player gain from securing *increases*:

$$J^*_{\mathbb{II}}(\{N,N\})-J^*_{\mathbb{II}}(\{S,N\})\leqslant J^*_{\mathbb{II}}(\{N,S\})-J^*_{\mathbb{II}}(\{S,S\})$$

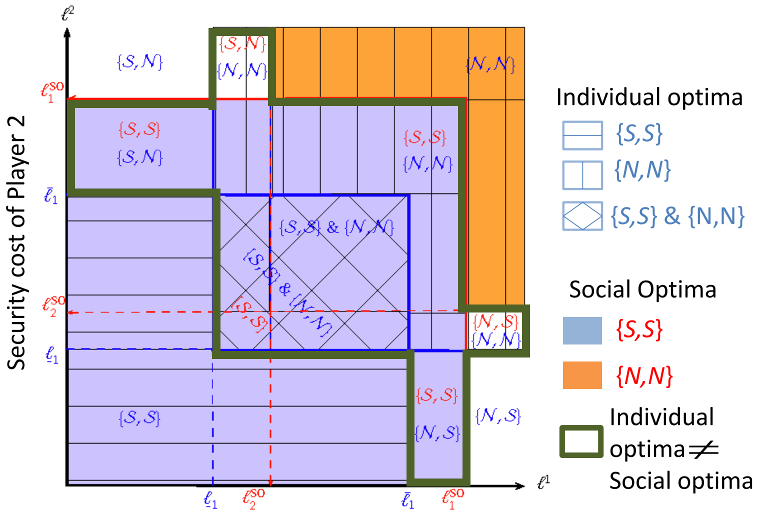
Decreasing incentives

If a player secures, other player gain from securing *decreases*:

$$J^*_{\mathbb{II}}(\{N,N\})-J^*_{\mathbb{II}}(\{S,N\})>J^*_{\mathbb{II}}(\{N,S\})-J^*_{\mathbb{II}}(\{S,S\})$$

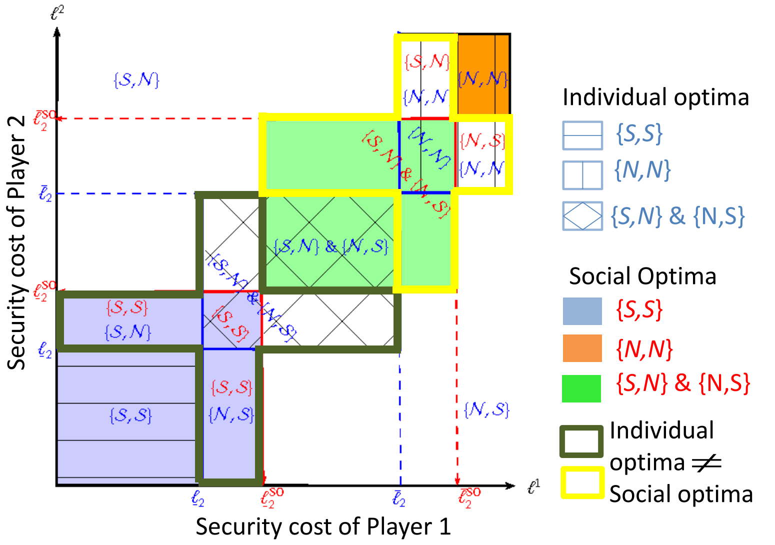
Individual optima [Nash equilibria] and social optima

Theorem [Increasing incentive case]



Individual optima [Nash equilibria] and social optima

Theorem [Decreasing incentive case]



Outline

Motivation: Cyber-Security

Sensor networks & Networked Control Systems (NCS)

NCS vulnerabilities

Cyber-security for NCS

1. Threat assessment
2. Attack diagnosis
3. Resilient control

Conclusions and ongoing work

Economics of NCS security and reliability

NCS security & reliability

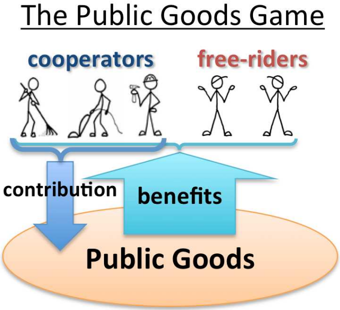
- Security failures (attacks S) and reliability failures (faults R) are difficult or costly to distinguish
- Goal: Model interdependent system failures F

$$\Pr(S \cap R \mid F) \neq \Pr(S \mid F)\Pr(R \mid F)$$

Courtesy: C. Goldschmidt (Symantec)

Negative externalities

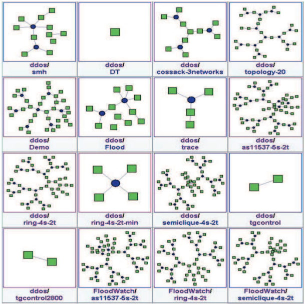
- Public goods game
- Information asymmetries
- Property right deficiencies & high enforcement costs
- Goal: Develop mechanisms to reduce NCS incentive suboptimality



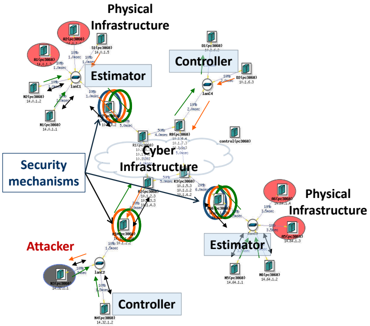
NCS security experimentation using DETER testbed

Experiments for networked infrastructure

- Testing
- Validation



Network topologies



Cyber-Security Testbed

cyber-DEfense Technology Experimental Research (DETER) Testbed

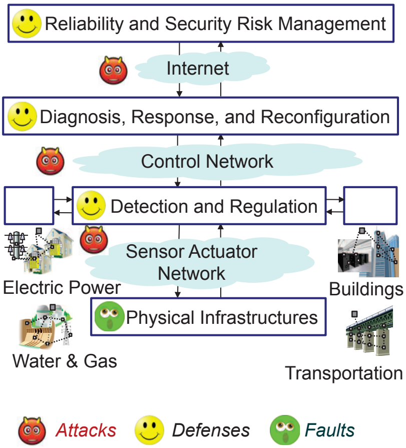
Towards a theory of high confidence NCS: Action Webs

Cyber-Security

- Assessment, detection & response
- Stealthy attacks
- Improved diagnostic schemes

Resilient Control

- Networked and fault-tolerant control
- Fundamental limitations
- Scalable resilient control algorithms
- Incentive mechanisms for security



Thank you for your attention

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